

Numerical and Experimental Investigations on the Hydrodynamic Performance of a Tidal Current Turbine

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Abstract. In this paper, numerical and experimental investigations are presented on the hydrodynamic performance of a horizontal tidal current turbine (TCT) designed and made by our Dalian University of Technology (DUT) research group. Thus it is given the acronym: DUTTCT. An open source CFD solver, called PimpleDyMFoam, is employed to perform numerical simulations for design analysis, while experimental tests are conducted in a DUT towing tank. The important factors, including self-starting velocity, tip speed ratio (TSR) and yaw angle, which play important roles in the turbine output power, are studied in the investigations. Results obtained show that the maximum power efficiency of the newly developed turbine (DUTTCT) could reach up to 47.6% and all its power efficiency is over 40% in the TSR range from 3.5 to 6; the self-starting velocity of DUTTCT is about 0.745m/s; the yaw angle has negligible influence on its efficiency as it is less than 10°.

1. Introduction

Tidal current energy has been receiving more and more attention since the late 1990's, mainly due to four reasons: the increasing demand for electricity from all human activities; the depletion of fossil energy; the increasingly stringent regulations on CO₂ emission due to climate change considerations and the last, also the most important one, the significant improvement of energy conversion technology [1-7]. The technology of energy conversion in the specialized field of tidal current energy is different from that of the tidal barrage, which is used to exploit the resources of the tidal range. The tidal current energy is harnessed by an underwater turbine located in a tidal current. Compared with the tidal barrage technology, the newly developed turbine technology has at least two advantages: 1) there is no need to build a barrage which requires a large amount of capital investment; 2) there is little negative impact on the environment and ecology in the neighborhood of the turbine.

The DUTTCT is a horizontal TCT which is designed and made by the DUT research group [8]. The DUTTCT is designed for use in the Bohai sea and the Huanghai sea in China, where there is low tidal current velocity ranging from 1m/s to 2m/s. At the current stage, the turbine is only designed for the purpose of theoretical and experimental studies. Numerical and experimental investigations have been conducted for examining the turbine hydrodynamic performance. Here the methods and results of the investigations are detailed in this paper.



2. Experimental Tests

The sketch of the DUTTCT impeller is shown in Figure 1, and its detailed parameters are shown in Table 1.

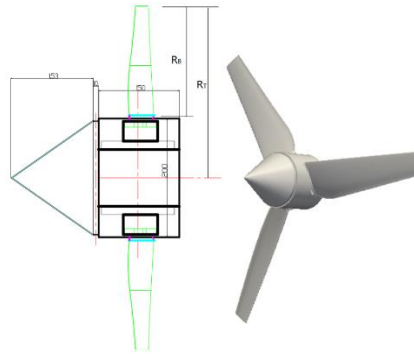


Figure 1. The sketch of DUTTCT impeller (left: geometry design; right: 3D model)

Table 1. The blade parameters of DUTTCT

item	parameters
Radius of impeller	$R_T=0.57\text{m}$
Length of blade	$R_B=0.47\text{m}$
Number of blades	$Z_T=3$
Swept area	$S_T=1.02\text{m}^2$

According to the experiments planned, in each TSR and yaw experiment, a predetermined flow speed is prescribed, and the torque of magnetic powder brake is then adjusted in order to obtain the required turbine rotating speed, thus the predetermined TSR. The signals of rotational speeds and torques during the whole process are recorded. The time averaged torque and rotating speed are used in experimental data analysis. The characteristic curves of energy conversion efficiency vs. tip speed ratio are shown in Figure 2.

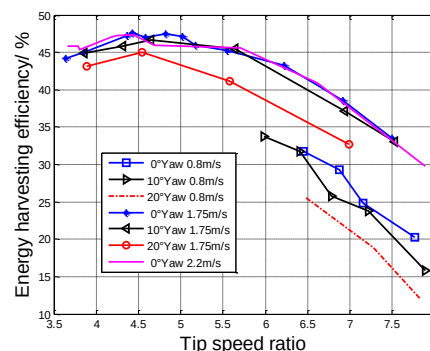


Figure 2. Efficiencies versus TSR for the DUTTCT.

The results show that energy conversion efficiency increases as TSR increases from 3.5 to 4.5 and then decreases as TSR further increases from 4.5 to 7.5. The optimum tip speed ratio is about 5 for the proposed turbine and the corresponding efficiency is 47.6% in the experiment. The lowest tip speed ratio is limited to 3.64 since the corresponding rotation speed, 110.6 rpm, is beyond the measurement range of the system.

Yaw effects are also investigated in this section. There are two sets of data for yaw effects obtained

by experiments corresponding to incoming velocities at 0.8m/s and 1.75m/s, respectively. The yaw angle for each incoming flow is set to 0° (no yaw angle), 10° and 20°, respectively. Figure 2 shows that energy conversion efficiency with 10° yaw, decreases slightly, by less than 1%, compared with the corresponding result of the zero-yaw case for an incoming velocity at 0.8 m/s. As for the case of incoming velocity at 1.75 m/s, the efficiency value does not decrease too much, by only about 2-3%, compared with the value of zero-yaw angle. There is a maximum value, at about 45% with TSR = 4.5 for all cases. When the yaw angle increases to 20°, the situations for the two incoming velocities are very different and their efficiency difference is large by comparison with the results of lower yaw angles. For example, for the case of incoming velocity at 0.8 m/s, the profile of efficiency at 20° yaw angle is almost parallel to that of zero yaw angle and the efficiency of the former is lower than the latter by about 5-6%. With incoming velocity at 1.75 m/s and a yaw angle of 20°, different from the smooth characteristic curves for zero yaw angle or 10° yaw angle as TSR varies from 3.5 to 6, a sharp profile of efficiency is obtained for the same TSR range. These indicate that larger yaw angles will have greater negative impacts on the conversion of energy, which should be avoided during operations.

3. Numerical Simulations and Investigations

Numerical simulations and investigations are conducted after the experiment for the purpose of mutual validation with experimental data and supplementing incomplete experimental data, as well as for the in-depth analysis of flow patterns. For example, there is a lack of data for working characteristic curves as TSR is less than 3.64 in the experiment due to the mismatch of magnetic powder brake.

In this paper, the PimpleDyMFoam, which is an ALE solver based on the hybrid PISO-SIMPLE (PIMPLE) numerical solution algorithm and dynamic meshes (DYM) with the AMI from the open source software OpenFOAM4.x [9] and its predecessor called TurboDyMFoam, is used to perform the numerical simulations. In the following subsections, the details of the governing equations for fluid flows used in the software and numerical simulations could be found in Refs. [10-14].

3.1. Computational domain of the DUTTCT

Figure 3 shows the rotation direction of the blades and the arbitrary mesh interface (AMI) boundary in the computational domain. Pink cylinder denotes the whole computational domain, the surface of yellow green cylinder the AMI boundary, and the red part the impeller. The dimensions of the computational domain are shown in Table 2.

Table 2 The sizes of computational domain

item	sizes
Diameter of outer cylinder	$D_O=5\text{m}$
Height of outer cylinder	$H_O=8.5\text{m}$
Diameter of inner cylinder	$D_i=3.2\text{m}$
Height of inner cylinder	$H_i=4.6\text{m}$
Diameter of AMI cylinder	$D_{AMI}=2\text{m}$
Height of AMI cylinder	$H_{AMI}=0.5327\text{m}$

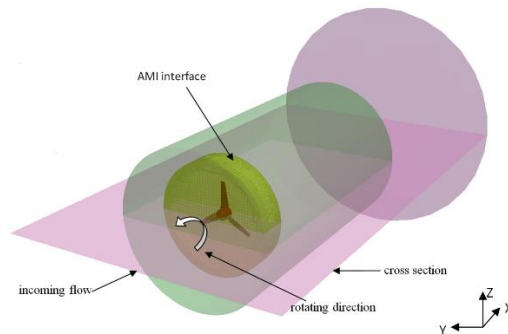


Figure 3 The sketch of AMI for DUTTCT in computational domain.

(The pink cylinder denotes the computational domain; the yellow green cylinder surface represents the AMI; the green cylinder indicates the refinement domain around the turbine and wake region)

3.2. The simulation cases

In the simulations performed to obtain its characteristic curves, both incoming flow velocity and rotational angular velocity are fixed in each simulation and the TSR is varied from 2 to 7 which are summarized in Table 3.

Table 3 Simulation cases for working characteristic curves

Case number	Current speed ($\text{m}\cdot\text{s}^{-1}$)	Tip Speed Ratio (t)
Case-2-c-t* 1-255	1,1.25,1.5,1.75,2, 0	2,2.5,3,3.5,4, 4.5,5,5.5,6,6.5,7

* Note: the affiliated definitions of case-2-c-t: '2' denotes working a characteristic simulation case; 'c' represents the current speed and 't' denotes the tip speed ratio. For example, case-2-1.25-2.5 means the working characteristic simulation case with a current speed of 1.25 m/s and a tip speed ratio of 2.5. With those current speeds and TSRs shown in Table 3, there are totally 55 cases for working characteristic simulations.

3.3. Numerical results

The working characteristic curves show three most important factors of the turbine: the highest efficiency of the turbine; the optimal TSR; and the high efficiency range of TSR. After the completion of all simulation cases, the characteristic curves of the DUTTCT are summarized in Figure 4. It shows that the highest efficiency is about 45% at an optimal TSR of 5.5, and for TSR ranging from 3.5 to 7, the efficiency of the DUTTCT is above 40%. The output efficiency does not show significant variations with various incoming velocities. For the purpose of comparison, those experimental data given in the towing tank experiment are also plotted in Figure 4. A good agreement between the simulation and experimental results is obtained for larger TSRs from TSR=5. However, the efficiencies obtained from experiment shown in Figure 4 are slightly larger than the numerical results in the range from TSR=3 to 5. Nevertheless, based on the curves obtained in Figure 4, the DUTTCT has indeed good working performance with various low incoming velocities in a wide range of TSRs.

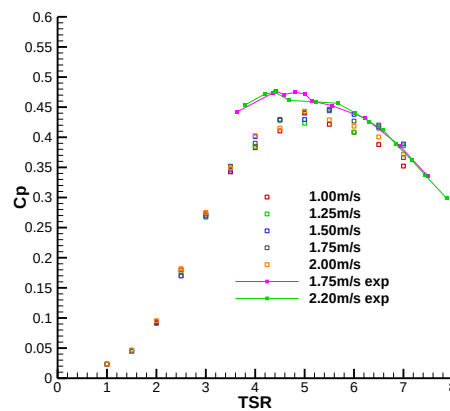


Figure 4. The working characteristic curves of the DUTTCT.

4 Conclusions and Discussions

In this paper, the hydrodynamic performance of the DUTTCT has been investigated experimentally and numerically. The findings obtained in the numerical and experimental investigations are very valuable for further improvement of the turbine performance and also provide valuable experience for future research work on tidal current turbines. The major conclusions about the DUTTCT are as follows:

1) The results show that the maximum power conversion efficiency of the DUTTCT could reach up to 47.6% and all the power efficiencies are over 40% for TSRs ranging from 3.5 to 6. Its self-starting velocity is about 0.745m/s, while the self-starting torque is about 2 Nm. The yaw angle does not affect its efficiency significantly when it is less than 10°. The DUTTCT has good working performance with low free-stream velocities in a wide range of TSRs.

2) Numerical simulations and experiment tests should be conducted simultaneously to complement and validate each other. For example, the power characteristic curves obtained from experiments lack lower-range TSR values because of the mismatched magnetic powder brake. However, numerical simulation results provide valuable low range TSR data.

Acknowledgement

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Reference

- [1] Uihlein A. and Magagna D. Wave and tidal current energy - A review of the current state of research beyond technology. *Renewable and Sustainable Energy Reviews*, 2016, Vol.58, 1070-1081.
- [2] Liu H.W., Ma S., Li W., Gu H.G., Lin Y.G., Sun X.J. A review on the development of tidal current energy in China. *Renewable and Sustainable Energy Reviews*, 2011, Vol.15(2), 1141-1146.
- [3] Li D., Wang S.J., Yuan P. An overview of development of tidal current in China: Energy resource, conversion technology and opportunities. *Renewable and Sustainable Energy Reviews*, 2010, 14, 2896-2905.
- [4] Li, W., Zhou H.B., Liu H.W., Lin Y.G., Xu Q.K. Review on the blade design technologies of tidal current turbine. *Renewable and Sustainable Energy Reviews*, 2016, 63, 414(9)
- [5] Li Y. On the definition of the power coefficient of tidal current turbines and efficiency of tidal current turbine farms. *Renewable Energy*, Volume 68, August 2014, 868-875.

- [6] Zhao Y. and Su X.H. Tidal Energy: Technologies and Recent Developments. IEEE International Energy Conference& Exhibition, Bahrain, 18-22 December 2010, 618-623.
- [7] Zhou Z.B., Benbouzid M., Charpentier J.F., Scuiller F., Tang T.H. Developments in large marine current turbine technologies - A review. Renewable and Sustainable Energy Reviews, 2017, 71, 852-858.
- [8] Zhang K.L. Numerical Study of Horizontal Tidal Current Turbine by using PimpleDyMFoam. Dalian University of Technology, 2013, Master thesis.
- [9] OpenFOAM. OpenFOAM Programmer's Guide. 2011.
- [10] Mathematics, Numerics, Derivations and OpenFOAM®, Tobias Holzmann, Book, December 2016, DOI: 10.13140/RG.2.2.27193.36960
- [11] Jasak, H. (1996). Error analysis and estimation for the finite volume method with applications to fluid flows. PhD thesis in Imperial College: University of London.
- [12] Jasak H. and Gosman A.D. Element residual error estimate for the finite volume method. Computers and Fluids, 2003, 32(2), 223-248.
- [13] Jasak H., Weller H.G., Gosman A. D. High resolution NVD differencing scheme for arbitrarily unstructured meshes. International Journal for Numerical Methods in Fluids, 30 September 1999, 31(2), 431-449.
- [14] Weller H.G., Tabor G., Jasak H., Fureby C. A tensorial approach to computational continuum mechanics using object-oriented techniques. Computers in Physics, November 1998, 12(6), 620-631.